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Resumen / Estudiamos la correlación entre masa estelar y metalicidad estelar en el conjunto de simulaciones cosmológicas hidrodinámicas *Evolution and Assembly of GaLaxies and their Environments* (EAGLE). A una dada masa estelar, las galaxias simuladas con metalicidades estelares menores muestran, en promedio, fracciones de gas mayores, tasas de formación estelar específicas mayores y poblaciones estelares más jóvenes. La retroalimentación al medio por núcleos activos de galaxias parece jugar un rol importante en la determinación de la metalicidad estelar a masas altas. En general, los sistemas simulados siguen una anticorrelación bien definida entre metalicidad estelar y fracción de gas, la cual no evoluciona significativamente con el corrimiento al rojo. Todas estas tendencias son consistentes con hallazgos previos respecto de la metalicidad del gas en regiones de formación estelar en EAGLE.

Abstract / We study the correlation between stellar mass and stellar metallicity in the Evolution and Assembly of GaLaxies and their Environments (EAGLE) suite of cosmological hydrodynamical simulations. At a given stellar mass, simulated galaxies with lower stellar metallicities show, on average, higher gas fractions, higher specific star formation rates and younger stellar populations. Active galactic nuclei feedback seems to play an important role on the determination of the stellar metallicity at high stellar masses. In general, simulated systems follow a well-defined anticorrelation between stellar metallicity and gas fraction, which does not evolve significantly with redshift. All these trends are consistent with previous findings regarding the metallicity of the star-forming gas in EAGLE.

Keywords / galaxies: abundances — galaxies: evolution — galaxies: formation — galaxies: star formation — cosmology: theory

1. Introduction

The study of the chemical abundances of galaxies is a topic of great interest in the community as it can help to constrain galaxy formation models (e.g. Finlator, 2017). In the local Universe, there is a well-defined correlation between gas-phase oxygen abundances ($\mathrm{O/H}|_{\mathrm{gas}}$) and stellar masses ($M_*$) of galaxies in such a way that more massive systems are more metal-enriched (e.g. Tremonti et al., 2004). The $M_* - \mathrm{O/H}|_{\mathrm{gas}}$ relation seems to evolve with redshift (z) in the sense that galaxies of similar masses were less metal-enriched in the past (e.g. Maiolino et al., 2008).

In last years, different authors suggested that the $M_* - \mathrm{O/H}|_{\mathrm{gas}}$ relation may be the projection on to two dimensions of a more fundamental relation (FMZR) between M_*, $\mathrm{O/H}|_{\mathrm{gas}}$ and star formation rate (SFR) (e.g. Mannucci et al., 2009). Other authors claimed that the FMZR might be a consequence of a more fundamental correlation between M_*, $\mathrm{O/H}|_{\mathrm{gas}}$ and gas fraction (f_{gas}) (e.g. Bothwell et al., 2013).

During the last decades, different theoretical models and simulations have tried to provide light into the origin of metallicity scaling relations (e.g. De Rossi et al., 2015; Bahé et al., 2017). In a recent work, (De Rossi et al., 2017) investigated different correlations between metallicities and other global properties of galaxies in the EAGLE simulations (Schaye et al., 2015). These authors focused mainly on the analysis of the star-forming (SF) gas metallicities, finding good agreement between some observed trends and predictions from a high-resolution version of the simulations. In the current article, we extend this previous work by analysing in more detail the metallicities associated to the stellar component (Z_*) of EAGLE galaxies.

2. Simulations

The EAGLE suite (Schaye et al., 2015; Crain et al., 2015) is a set of cosmological hydrodynamical simulations run in cubic, periodic volumes ranging from 25 to 100 comoving Mpc. These simulations were run using a modified version of the GADGET-3 code and adopting a Λ-CDM flat cosmology: $\Omega_\Lambda = 0.693$, $\Omega_\mathrm{m} = 0.307$,

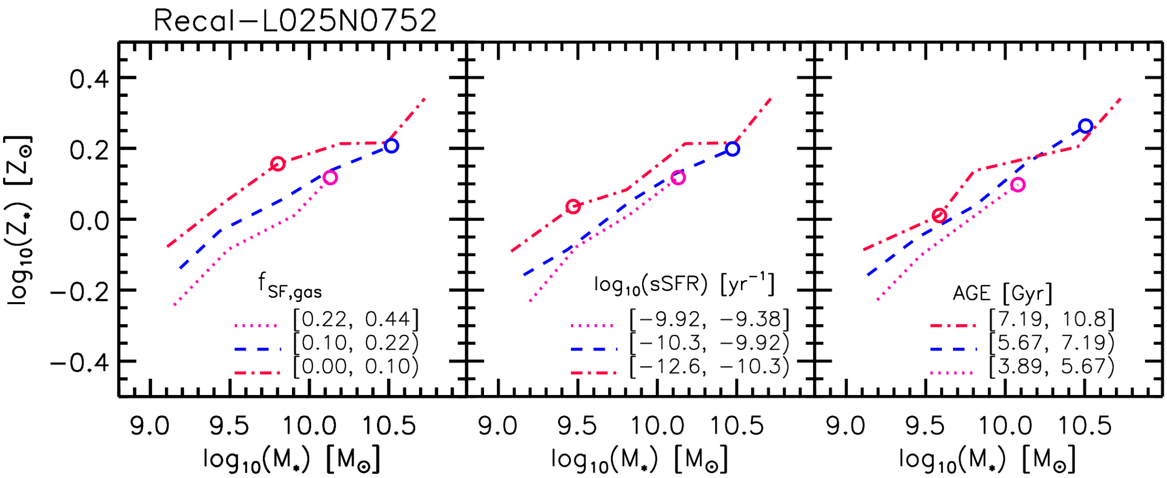

Figure 1: Median $M_* - Z_*$ relation at $z = 0$ binned in $f_{\rm SF,gas}$ (left panel), sSFR (middle panel) and stellar mass-weighted mean age (right panel), as indicated in the figure. All considered mass bins contain $N_{\rm bin} \geq 5$ galaxies; less populated bins ($5 \leq N_{\rm bin} < 10$) are marked with a circle.

$\Omega_{\rm b} = 0.04825$ and $h = 0.6777$ (Planck Collaboration et al., 2014). The simulations implement state-of-the-art numerical techniques and subgrid models for radiative cooling, star formation, stellar mass loss and metal enrichment, energy feedback from star formation and active galactic nuclei (AGN) feedback, among others.

Unless otherwise specified, in this work, we present results obtained from the high-resolution simulation Recal-L025N0752, which predicts metallicity scaling relations in better agreement with some observed trends. This simulation tracks the evolution of an initial number of 752^3 particles per species within a box of side-length of L=25 comoving Mpc and assumes recalibrated parameter values to improve the match to the observed $z \sim 0$ galaxy stellar mass function when increasing the resolution (see Schaye et al. 2015, for details).

3. Results

De Rossi et al. (2017) found that EAGLE-Recal-L025N0752 simulation predicts a correlation between M_* and Z_* consistent with the observed behaviour (their Fig. 5). In this section, we explore secondary dependences of Z_* at a given M_*. We also analyse the role of AGN feedback on Z_* at high masses.

3.1. The $Z_* - M_*$ relation and its scatter

In Fig. 1, we show the $M_* - Z_*$ relation binned according to SF gas fraction ($f_{\rm SF,gas}$) (left panel), specific SFR (sSFR, middle panel) and stellar mass-weighted mean age (right panel), as indicated in the figure. The gas fraction is calculated as $M_{\rm SF,gas}/(M_{\rm SF,gas} + M_*)$, where $M_{\rm SF,gas}$ denotes the star-forming gas component. At a given M_*, lower Z_* can be associated, on average, to higher $f_{\rm SF,gas}$, higher sSFR and younger stellar populations. Similar trends were obtained by De Rossi et al. (2017) for SF gas-phase oxygen abundances ($\rm O/H|_{SF,gas}$) at $M_* < 10^{10.3}$ $\rm M_\odot$ (see their Fig. 8). We note, however, that the secondary dependences obtained for Z_* at a given mass are weaker than those previously found for $\rm O/H|_{SF,gas}$ in a similar mass range. This behaviour is consistent with a scenario in which the infall of metal-poor gas in low-mass galaxies leads to higher sSFRs and younger stellar populations in these systems.

According to our findings, Z_* exhibits a strong anticorrelation with $f_{\rm SF,gas}$ (Fig. 2). The $f_{\rm SF,gas} - Z_*$ relation does not evolves significantly with z and shows a moderate scatter. As $f_{\rm SF,gas}$ increases from ≈ 0 to ≈ 0.8, Z_* decreases by more than 1 dex. These results are consistent with those obtained by De Rossi et al. (2017) in the case of the SF-gas metallicities, which are also consistent with the so-called "universal metallicity relation" found by Zahid et al. (2014) in the context of empirical-constrained analytical models.

3.2. AGN feedback effects

In order to explore the impact of AGN feedback on the $M_* - Z_*$ relation, we need to focus on the trends at high masses and, thus, we employed the intermediate resolution simulations L050N0752. These simulations were run in a volume of side length of 50 comoving Mpc including 752^3 particles. Four subsets of simulations were studied comprising four models featuring variations of the temperature increment of stochastic AGN heating ($\Delta T_{\rm AGN}$): NOAGN (AGN effects suppressed entirely), Ref (reference model, $\Delta T_{\rm AGN} = 10^{8.5}$ K), AGNdT8 ($\Delta T_{\rm AGN} = 10^8$ K) and AGNdT9 ($\Delta T_{\rm AGN} = 10^9$ K) (see Schaye et al. 2015 and Crain et al. 2015, for a description of the simulations).

Fig. 3 shows that AGN feedback plays an important role on the determination of stellar metallicities at high masses, at least in these simulations. The slope of the $M_* - Z_*$ relation decreases with $\Delta T_{\rm AGN}$ and, when AGN feedback is completely suppressed, Z_* increases by up to 0.3 dex at $M_* \sim 10^{11}$ $\rm M_\odot$. As discussed in detail in De Rossi et al. (2017), AGN feedback leads to a decrease

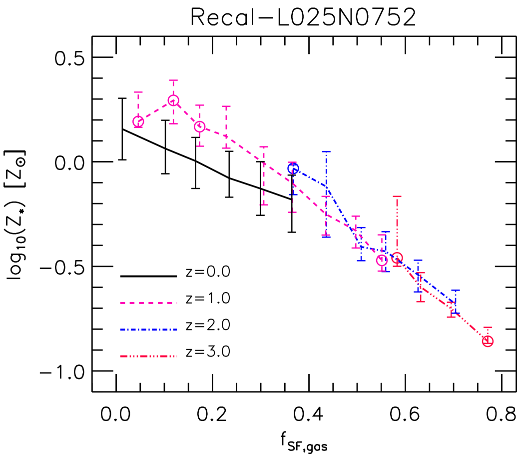

Figure 2: Stellar metallicity as a function of star-forming gas fraction for EAGLE galaxies at different z, as indicated in the figure. Curves depict the median relation and error bars, the 25th and 75th percentiles. The number of galaxies per bin is $N_{\rm bin} \geq 7$, with circles indicating less populated bins ($N_{\rm bin} = 7 - 9$).

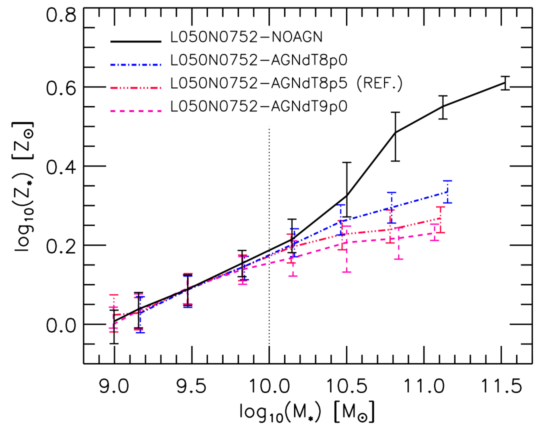

Figure 3: Simulated $M_* - Z_*$ relations at $z = 0$ for different models. Results obtained from simulations "L050N0752" with different AGN feedback parameters are presented: NOAGN (AGN feedback suppressed entirely), AGNdT8 ($\Delta T_{\rm AGN} = 10^8$ K), reference model ($\Delta T_{\rm AGN} = 10^{8.5}$ K) and AGNdT9 ($\Delta T_{\rm AGN} = 10^9$ K). Note that AGN effects set in above $M_* \sim 10^{10}$ M$_\odot$ (dashed vertical line).

in the metal content of galaxies by quenching the star formation process and generating the ejection of metal enriched gas from galaxies. Net metal dilution might also have a (minor) impact on the metal enrichment of massive AGN-host galaxies.

4. Summary

We studied stellar metallicity scaling relations in the EAGLE suite of cosmological hydrodynamical simulations. We focused mainly on the high-resolution simulation run that implements the so-called recalibrated model. At a given M_*, simulated galaxies with lower Z_* tend to have higher SF gas fractions, higher sSFR and younger stellar populations. These trends are stronger at $M_* < 10^{10.3}$ M$_\odot$. In general, we found a strong anticorrelation between Z_* and SF gas fraction, in agreement with the existence of the so-called "universal metallicity relation" reported by Zahid et al. (2014).

To explore the impact of AGN feedback, we employed intermediate resolution simulations in which the AGN feedback temperature is varied. Our findings suggest that AGN feedback plays an important role on the determination of the slope of the $M_* - Z_*$ relation at $M_* > 10^{10}$ M$_\odot$. Thus, the study of the mass-metallicity relation at high masses could help to constrain AGN feedback models.

For more details about this work and results for SF gas-phase metallicities, the reader is referred to De Rossi et al. (2017).

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